ANALYSIS OF THE POTENTIAL OF USING PHOTOVOLTAIC AND WIND-TURBINE ENERGY SYSTEMS IN THE CANADIAN RESIDENTIAL SECTOR

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ABSTRACT

The Canadian residential sector contributes approximately 80 megatonnes (Mt) of greenhouse gases (GHG) to the environment each year. With the ratification of Kyoto protocol, Canada has committed to reduce its GHG emissions by at least five percent between 2008 and 2012 on the basis of its 1990 emission levels. To meet this target Canada has to evaluate and exploit every feasible meaning to reduce the fossil fuel energy consumption and the consequent GHG emissions. In this work, test-case Canadian houses were modeled in the building energy simulation software ESP-r. Requisite housing stock data was extracted from Canada's most comprehensive residential end-use energy surveys. As a source of alternate energy, photovoltaic (PV) and wind-turbine energy systems were assessed for their potential contribution to the energy and GHG savings. The results show that in two out of the four test-case houses 100 percent electricity requirements could be met by using technologies.

KEYWORDS

Greenhouse gases (GHG), Kyoto Protocol, Photovoltaic systems, Wind-turbine energy systems, ESP-r

INTRODUCTION

Canada has one of the coldest climates in the world and there is a prevalence of single-family dwellings across this country. As a consequence the total end-use energy consumption of Canada is very high. Figure 1 shows the trend of Canadian GHG emissions between years 1990 to 2003. In year 2004 a total of 8543 Petajoules (PJ) of energy was consumed, with 1421 PJ used in residential sector. The GHG emissions for the residential sector in 2004 were 77 Mt (NRCan 2006).

Addressing the worldwide concern over the potential undesirable climatic changes across the globe an international treaty known as the Kyoto Protocol was signed. Under the commitment of this protocol, Canada promised to reduce its GHG emissions by six percent by the year 2012 based on its emission levels of 1990. To meet this target, Canada has to evaluate and exploit all feasible measures to reduce fossil fuel energy consumption and the associated GHGs.

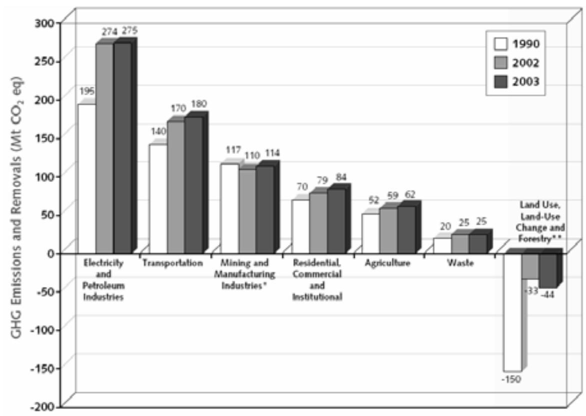

Figure 1 Trend of the Canadian GHG emission from 1990 to 2003 (Environment Canada, 2005)

In this paper the results of a study done to assess the potential of using building integrated PV and roof mounted wind-turbine energy systems in the test-case Canadian residential models have been presented. The test-case house models were developed and simulated with PV and wind-turbine energy systems in the state of the art building energy simulation tool ESP-r.

SELECTING TYPICAL CANADIAN TEST-CASE HOUSES

The typical Canadian test-cases houses were generated using three Canadian housing stock databases, namely SHEU (Statistics Canada 1993), EnerGuide (NRCan

2005-ii) and New Housing Survey (NRCan 1997), respectively.

The SHEU database was firstly segregated into four regional groups i.e. Atlantic, Central, Prairies and West, respectively. Atlantic region contained the provinces of Newfoundland, Prince Edward Island, Nova Scotia and New Brunswick. Central region contained Quebec and Ontario. Prairies contained Manitoba, Saskatchewan and Alberta while West encompassed British Columbia. The data in SHEU contains associated weights of all houses it represents. For the present study only single detached houses were considered. All single detached houses in SHEU database falling in each region were firstly categorized based on the provinces they belonged to. Then the database of each province was classified based on the vintage groups its houses fell under. Four vintage groups were defined, which were the houses built 'before 1941', 'between 1941-1960', 'between 1961-1977' and 'after 1977', respectively. Houses falling in each vintage group were further classified based on the principal fuels used for their space heating. The principal space heating fuels considered in this study were oil, natural gas and electricity, respectively.

Once the SHEU database was classified in the categories stated above, one of the most representative test-case houses was chosen from each region. The sole criterion of selection was the weighting factors the test-case houses carried, and the houses carrying highest weight compared to others were chosen. The selected test-case houses were simulated with the weather file of the most densely populated city in that region. The four selected test-case houses have been presented in Table 1.

Table 1 Representative Test-case houses

Test-case houses	Region	Location	Vintage	Space Heating Fuel
1	Atlantic	Halifax	1961-1977	Oil
2	Central	Toronto	After 1977	Natural Gas
3	Prairies	Calgary	1961-1977	Natural Gas
4	West	Vancouver	1961-1977	Natural Gas

TEST-CASE HOUSES DEVELOPMENT

After test-case houses were selected for each region, different constructional and thermal characteristic and attributes, like floor areas, wall insulations, heating set-points, space heating equipment efficiencies, domestic hot water (DHW) systems, window types, orientation etc. of each house were found. Most of the required information was available in SHEU database, while remaining information was supplemented from EnerGuide and New Housing Survey.

Some characteristics of the test-case houses are presented here:

TEST-CASE HOUSES 1:

- Located in Halifax.
- Single storey house with living area of 1250 ft^2 (excluding basement).
- Uses the furnace with flame retention head for space heating and is using oil. Equipment has efficiency of 78.7 percent.
- DHW plant is conventional with pilot, having efficiency of 56 percent.
- Construction details:
  - Main Wall RSI: 1.84
  - Foundation RSI: 0.83
  - Ceiling RSI: 3.19
- Has a full heated basement.
- It has three occupants.
- Infiltration: 6.84 @ 50Pa
- Total glazed area of 8.69m^2 with double glazed windows.
- Has an annual 'appliance and lighting' electric consumption of 9,818 kWh.

TEST-CASE HOUSES 2:

- Located in Toronto.
- Two-storey house with living area of 1750 ft^2 (excluding basement).
- Uses the furnace with continuous pilot for space heating and is using natural gas. Equipment has efficiency of 82.4 percent.
- DHW plant is conventional with pilot, having efficiency of 55.6 percent.
- Construction details:
  - Main Wall RSI: 2.28
  - Foundation RSI: 1.79
  - Ceiling RSI: 5.06
- Has a full heated basement.

- It has three occupants.
- Infiltration: 4.56 @ 50Pa
- Total glazed area of 9.486m^2 with double glazed windows.
- Has an annual ‘appliance and lighting’ electric consumption of 9,613 kWh.

TEST-CASE HOUSES 3:

- Located in Calgary.
- Single storey with living area of 1250 ft^2 (excluding basement).
- Uses the furnace with continuous pilot for space heating and is using natural gas. Equipment has efficiency of 74.9 percent.
- DHW plant is conventional with pilot, having efficiency of 55 percent.
- Construction details:
  - Main Wall RSI: 1.91
  - Foundation RSI: 1.25
  - Ceiling RSI: 4.23
- Has a heated full basement.
- It has three occupants.
- Infiltration: 4.32 @ 50Pa
- Total glazed area of 7.116m^2 with double glazed windows.
- Has an annual ‘appliance and lighting’ electric consumption of 10,510 kWh.

TEST-CASE HOUSES 4:

- Located in Vancouver.
- Single storey with living area of 1250 ft^2 (excluding basement).
- Uses the furnace with continuous pilot for space heating and is using natural gas. Equipment has efficiency of 77.3 percent.
- DHW plant is conventional with pilot, having efficiency of 51.1 percent.
- Construction details:
  - Main Wall RSI: 1.75
  - Foundation RSI: 1.82
  - Ceiling RSI: 3.91
- Has a heated full basement.
- It has three occupants.
- Infiltration: 8.07 @ 50Pa
- Total glazed area of 18.972m^2 with 65% single glazed windows and 35% double-glazed windows.
- Has an annual ‘appliance and lighting’ electric consumption of 17,301 kWh.

DEVELOPMENT OF ELECTRICAL LOAD PROFILES

The occupant driven appliance and lightning electricity demand plays a very important role in the electricity usage pattern of the house, having consequences on building thermal.

The typical Canadian residential electricity demand profiles developed by Good et al. (2004) were used to determine the shape of the electricity load curves for the selected test-case houses, while their magnitudes were taken from the Neural Network based residential appliance and lightning electricity demands by Aydinalp (2002).

Figure 2 shows a typical seasonal averaged daily electricity load profiles for the test-case house in Vancouver. The seasons are defined as winter (December to February), spring (March to May), summer (June to August) and fall (September to November), respectively.

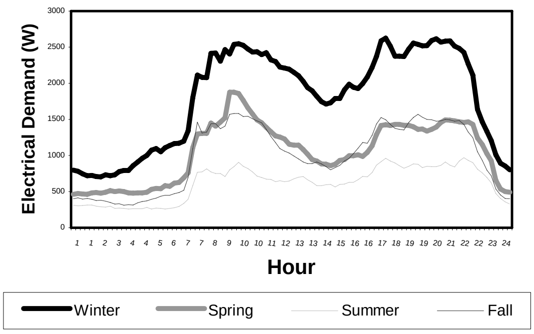

Figure 2 Daily electricity load profiles for test-case house model 3 for four seasons

BASE-CASE SIMULATIONS

Once the models were developed in ESP-r and electrical load profiles properly linked to them, annual simulations were run to determine the required furnace sizes for the test-case houses.

Once the furnace sizes were determined and the ESP-r models were updated with new furnace sizes, the simulations were run again. These set of simulations were termed as ‘base-case simulations’. These simulations assessed the thermal and electrical behaviour of the house at its current status, i.e. without any renewable energy component attached to it. The results of these simulations provided a basis for comparison of test-case houses behaviour with renewable energy components attached to it.

SELECTION OF SIZES OF PV AND WIND-TURBINE ENERGY SYSTEMS

After running base-case simulation for the selected test-case houses, the appropriate sizes of the PV and wind-turbine energy systems. For this study the BP_saturn_36cell PV module and existing wind-turbine models in ESP-r were used. This PV module has an area of 0.621m^2 and has a power output of 85 Watts, rating its power-output to area ratio the highest among other PV models available in ESP-r.

For PV system, the size selection guidelines from NRCan (2002) were used. The total HVAC and non-HVAC electrical loads were summed up and divided by the average peak-sunshine hours of the simulation city in the months of September and December.

Table 2 The estimated PV array sizes for the selected test-case houses

Test-case houses	Daily electrical demand (kWh)	Average Peak Sunlight Hours	Required array size (kW)
1	31.5	3.45	9.1
2	30.4	3.31	9.2
3	33.4	3.66	9.1
4	55.5	3.75	14.8

The estimated required size in all the test-case houses resulted in the size of arrays that exceed the roof dimensions. Hence the allowable maximum number of modules was calculated based on the available roof area. This resulted in an array of capacity of 7.8 kWp for test-case houses 1, 3 and 4 respectively, while an array of capacity of 5.4 kWp for test-case houses 2. If the roofs of selected test-case houses were facing east or west, both sides were tested for PV performance, and the orientation that gave maximum output was selected. In case when the roof of the test-case house was facing south, the array was installed on the south-facing roof. In this way the PV array sizes and orientations were finalized.

For the selection of roof-mounted wind-turbine energy systems, the turbine area and installation limitations outlined by Canadian Wind Energy Association (CanWEA 2006) led to the selection of two sizes of 600W and 1kW capacity respectively.

Hence each of the test-case houses was simulated for its suitable PV array sizes with two wind-turbine sizes, resulting in two sets of simulations for each house. The set of simulations with PV and wind-turbine installed in the house models were called hybrid-case simulations.

SIMULATION RESULTS

The base case annual simulation results for the four test houses have been presented in Table 3. The results presented here are assuming either battery storage or net-metering facility because there are mismatches in the occurrence of timings of the electricity demand of the house and the power production by the renewable energy systems. With the use of net-metering facility or on-site battery storage the excess can be sold to the grid or stored in the battery and imported when needed.

The CO_2 equivalent emission factor for electricity generation in gCO_2eq/kWh for Vancouver is 24, Calgary is 861, Toronto is 222 and Halifax is 759, respectively (Environment Canada 2006). To date the time-of-usage rates are available only for Nova Scotia and Ontario, hence electrical results of houses in Halifax and Toronto are presented for both flat and time-of-usage rates.

Table 3 The base-case annual simulation results for the four test-case models

Test Case House	1	2	3	4
Electricity Consumption (kWh)	10335	9994	10966	18237
SH (GJ)	121.9	85.7	112.9	128.4
DHW GJ)	13.6	13.6	13.8	13.7
TOU Cost (CAD)	694	1063	-	-
Flat Rate Cost (CAD)	1047	999	845	1154
GHG_E (Tonnes)	7.8	2.2	9.4	0.5
GHG_{TE} (Tonnes)	7.4	5.6	7.1	7.9
GHG_{Total} (Tonnes)	15.2	7.8	16.5	8.4

The results of the simulations with PV and wind-turbines for the four test-case houses have been presented in Tables 4 to 7.

Table 4 The hybrid-case annual simulation results for Test-Case House 1 in Halifax

Test-Case House 1	**7.8 kWp PV array**	
	600W WT	**1kW WT**
PV output (kWh)	9123	9123
WT output (kWh)	1003	1543
Total energy produced (kWh)	10126	10667
Surplus energy produced (kWh)	0	331
Net Import (kWh)	209	0
TOU Cost (CAD)	13	0
Flat Rate Cost (CAD)	21	0
GHG_E (Tonnes)	0.16	0
GHG_{Total} (Tonnes)	7.6	7.4

Table 5 The hybrid-case annual simulation results for Test-Case House 2 in Toronto

Test-Case House 2	**5.4 kWp PV array**	
	600W WT	**1kW WT**
PV output (kWh)	6647	6647
WT output (kWh)	1074	1686
Total energy produced (kWh)	7721	8333
Surplus energy produced (kWh)	0.0	0.0
Net Import (kWh)	2273	1661
TOU Cost (CAD)	227	166
Flat Rate Cost (CAD)	227	166
GHG_E (Tonnes)	0.5	0.4
GHG_{Total} (Tonnes)	6.1	5.9

Table 6 The hybrid-case annual simulation results for Test-Case House 3 in Calgary

Test-Case House 3	**7.8 kWp PV array**	
	600W WT	**1kW WT**
PV output (kWh)	10235	10235
WT output (kWh)	1125	1774
Total energy produced (kWh)	11360	12009
Surplus energy produced (kWh)	395	1044
Net Import (kWh)	0.0	0.0
Flat Rate Cost (CAD)	0.0	0.0
GHG_E (Tonnes)	0.0	0.0
GHG_{Total} (Tonnes)	7.04	7.0

Table 7 The hybrid-case annual simulation results for Test-Case House 4 in Vancouver

Test-Case House 4	**7.8 kWp PV array**	
	600W WT	**1kW WT**
PV output (kWh)	9376	9376
WT output (kWh)	673	976
Total energy produced (kWh)	10049	10351
Surplus energy produced (kWh)	0.0	0.0
Net Import (kWh)	8188	7885
Flat Rate Cost (CAD)	518	499
GHG_E (Tonnes)	0.22	0.21
GHG_{Total} (Tonnes)	8.18	8.17

DISCUSSIONS

Figures 3 to 6 show the typical averaged daily total electric power generated by PV and wind-turbine versus the total electricity consumption for four seasons for the test-case house 2, simulated in Toronto. The horizontal axes of these graphs represent the local time. The roof orientation for test-case house 2 is due south hence the PV output is symmetrical about the solar noon for all four seasons.

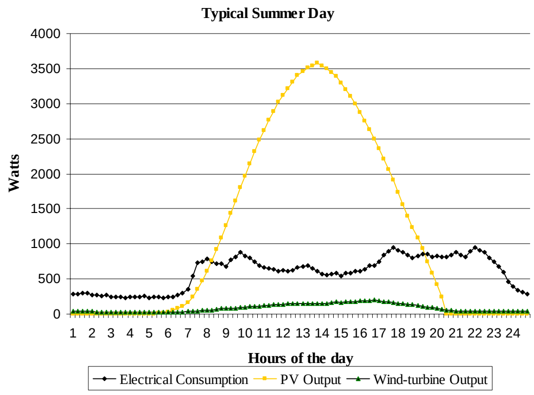

Figure 3 A typical summer day electricity consumption and output of PV and wind-turbine for test-case house 2 simulated in Toronto

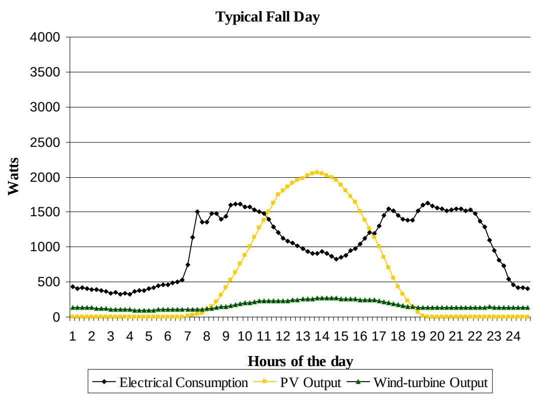

Figure 4 A typical fall day electricity consumption and output of PV and wind-turbine for test-case house 2 simulated in Toronto

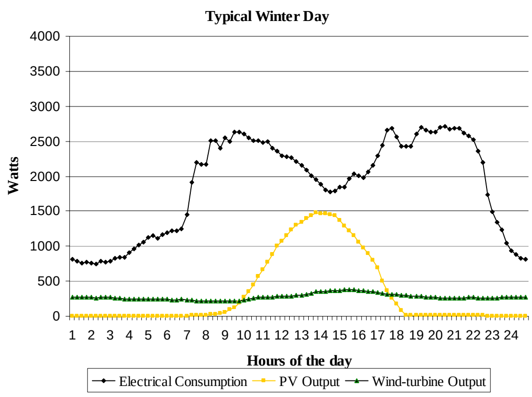

Figure 5 A typical winter day electricity consumption and output of PV and wind-turbine for test-case house 2 simulated in Toronto

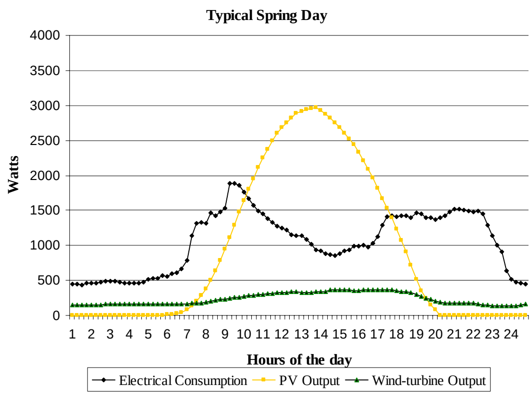

Figure 6 A typical spring day electricity consumption and output of PV and wind-turbine for test-case house 2 simulated in Toronto

As it can be seen in Figures 3 to 6, for different hours of the day during different seasons, either the renewable energy exceeds the demand or it contributes to meet a part of total electric load. During the time of the day when the renewable power is contributing to the demand, the net import from the grid is lower, resulting in lesser load on the utility grid. During the times when the renewable power is more than the demand, the surplus power can be sold to the local grid using net metering facility. Net metering policy allows homeowners to receive the full value of the electricity that their hybrid renewable electric systems produce, without having to install a battery storage system (U. S. Department of Energy 2007). If more electricity is produced than the home needs, the extra kilowatts are fed to the utility grid and the customer earns the credit at the wholesale power rate system (U. S. Department of Energy 2007).

Tables 8 to 11 present the percentage of electricty demand that is met using the designed hybrid PV and wind energy sytems and the percentage reduction in GHG emissions and cost of electricity for the test-case houses.

Table 8 Results summary for test-case house 1

Summary	PV & 600W WT	PV & 1kW WT
% Demand Met	97	100
% Reduction in GHG due to Electricity	97	100
% Reduction in overall GHG	49	51.4
% Saving in electricity cost at flat rate	97	100
% Saving in electricity cost at TOU rate	98	100

Table 9 Results summary for test-case house 2

Summary	PV & 600W WT	PV & 1kW WT
% Demand Met	77	83
% Reduction in GHG due to Electricity	77	83
% Reduction in overall GHG	22	24
% Saving in electricity cost at flat rate	77	83
% Saving in electricity cost at TOU rate	78	84

Table 10 Results summary for test-case house 3

Summary	PV & 600W WT	PV & 1kW WT
% Demand Met	100	100
% Reduction in GHG due to Electricity	100	100
% Reduction in overall GHG	57	57.3
% Saving in electricity cost at flat rate	100	100

Table 11 Results summary for test-case house 4

Summary	PV & 600W WT	PV & 1kW WT
% Demand Met	55	57
% Reduction in GHG due to Electricity	55	57
% Reduction in overall GHG	2.6	2.7
% Saving in electricity cost at flat rate	55	57

CONCLUSIONS

The hybrid-case simulation results for test-case house 1, located in Halifax show that with 7.82kWp PV array and 1kW wind turbine, all the annual electrical demands can be met. The can result in zero GHG emissions for that house.

The results for test-case house 2 show that with the use PV and wind-turbine technologies up to 83 percent annual electricity requirements can be met. This can result in the reduction of GHG emissions due to electricity generation by 77 (with 600 Watt wind-turbine) to 83 (with 1kW wind turbine) percent.

Test-case results for house 3 show that not only can the hybrid energy system fulfill annual energy demand and produce zero GHG emissions rather excess energy can earn him the credit of 30.44 CAD (with 600 Watt wind-turbine) and 80.50CAD (with 1kW wind-turbine), respectively at the flat selling rate of 7.71¢ per kWh.

Test-case house model 4 shows a potential of meeting up to 57 percent of annual electricity demand, resulting in potential reduction in GHG emissions due to electricity generation by 57 percent.
Hence, it can be seen from the simulation results that there is a huge potential of electricity generation by using PV and wind-turbine systems for Canadian residential sector. These renewable technologies not only result in production of onsite electricity but also have a pronounced effect on the GHG reduction.

NOMENCLATURE

Abbreviations

CAD	Canadian dollars
DHW	domestic hot water
GHG_E	GHG emissions due to electricity generation
GHG_{TE}	GHG emissions due to thermal energy generation
GHG_{Total}	Total GHG emissions
SH	space heating
TOU	Time of Usage electricity
WT	Wind turbine

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